



## **NASA SBIR 2021 Phase I Solicitation**

### **Z3.03 Development of Advanced Joining Technologies, Large-Scale Additive Manufacturing Processes, and Metal Recycling Technologies for On-Orbit Manufacturing**

**Lead Center: MSFC**

**Participating Center(s): GSFC, LaRC**

Scope Title:

**Development of Advanced Joining Technologies for On-Orbit Manufacturing**

#### **Scope Description:**

Technology development efforts are required to enable on-orbit servicing, assembly, and manufacturing (OSAM) for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets.

An in-space material welding capability is an important supporting technology for the long-duration, long-endurance space missions that NASA will undertake beyond the International Space Station (ISS). Historically, structures in space have been assembled using mechanical fastening techniques and modular assembly. Structural designs for crewed habitats, space telescopes, antennas, and solar array reflectors are primarily driven by launch considerations such as payload fairing dimensions and vibrational loads experienced during ascent. An in-space welding capability will greatly reduce constraints on the system imposed by launch, enabling the construction of larger, more complex, and more optimized structures. Welding is an essential complementary capability to large-scale additive manufacturing technologies being developed by NASA and commercial partners. Welding is also a critical capability for repair scenarios (e.g., repair of damage to a structure from micrometeorite impacts).

This subtopic seeks innovative engineering solutions to robotically weld materials, both fully autonomous and semiautonomous, for manufacturing in the unpressurized space environment. Current state-of-the-art (SOA) terrestrial welding methods such as laser beam, electron beam, and friction stir should be modified with an effort to reduce the footprint, mass, and power requirements for on-orbit applications.

Phase I is a feasibility study and laboratory proof of concept of a robotic welding process and system for on-orbit manufacturing applications. Targeted applications for this technology include joining and repair of components at the subsystem level, habitat modules, trusses, solar arrays, and/or antenna reflectors. The need to repair a

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damaged structure or build new structures may require the need to not only weld material but to cut and remove material. A process that can weld material is the priority, but a robust process with cutting and removal capabilities adds value. The Phase I effort should provide a laboratory demonstration of the welding process and its applicability to aerospace-grade metallic materials and/or thermoplastics, focusing on joint configurations that represent the priority in-space joining applications identified above. Work under Phase I will inform preliminary design of a mobile welding unit and a concept of operations for how the system would be deployed and operate in the space environment, with a focus on specific scenarios—for example, repair of a metal panel following micrometeorite damage, longitudinal welding of two metal curved panels, and welding of a truss to an adjacent truss. The Phase I effort should also provide an assessment of the proposed process operational capabilities (e.g., classes of materials that can be welded with the process, joint configurations that can be accommodated, and any expected impacts of the microgravity environment on joint efficiency relative to terrestrial system operation), volume, and power budget. A preliminary design and concept of operations are also deliverables under Phase I. Concepts for ancillary technologies such as post-process inspection, in situ monitoring, or robotic arms for manipulation of structures to be welded may also be included in the Phase I effort.

**Expected TRL or TRL Range at completion of the Project:** 3 to 5

**Primary Technology Taxonomy:**

Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing

Level 2: TX 12.4 Manufacturing

**Desired Deliverables of Phase I and Phase II:**

- Prototype
- Analysis
- Hardware

**Desired Deliverables Description:**

Phase I requires laboratory demonstration/proof of concept that (a) the system enables high-value applications of repair and assembly and (b) the system shows potential for being operated remotely with very little intervention/setup. A preliminary design and concept of operations are also deliverables under Phase I.

Phase II includes finalization of the design and demonstration of a ground-based prototype system.

Phase III would seek to evolve the technology toward a flight demonstration, either via a system mounted externally on the ISS, Exploration Crew Module (ECM), Gateway, OSAM-1, OSAM-2, lunar lander payload, or as a free-flyer.

**State of the Art and Critical Gaps:**

Unpressurized environment in-space manufacturing has primarily focused on fabrication of structures in the space environment. Welding is an essential supporting technology to these capabilities. Research on welding tapered off to some extent following the cancellation of the In-Space Welding Experiment (ISWE) for the space shuttle. With the emergence of the OSAM initiative, a renewed interest and focus on manufacturing structures in the space environment as an enhancing capability for long-duration missions, and as a way to remove design constraints imposed by payload fairings and launch loads, additional work on development of an in-space welding capability should be a priority. In-space welding represents an essential complementary technology to in-space fabrication techniques.

**Relevance / Science Traceability:**

The research requested through this solicitation is relevant to NASA programs, including (but not limited to) the following: ISS, Exploration Crew Module (ECM), Gateway, Lunar Base Camp, OSAM-1 and OSAM-2, in-Space Assembled Telescope (iSAT) and SmallSat.

**References:**

G. L. Workman and W. F. Kaukler, “Laser Welding in Space,” 1989.

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D. Tamir et al., "In-Space Welding: Visions and Realities," 1993.

B. E. Paton and V. F. LapchinskiĀ, "Welding in Space and Related Technologies," Cambridge International Science Publishing, 1997.

I. D. Boyd, R. S. Buenconsejo, D. Piskorz, B. Lal, K. W. Crane, and E. De La Rosa Blanco, "On-Orbit Manufacturing and Assembly of Spacecraft: Opportunities and Challenges," 2017.

S. Carioscia, B. A. Corbin, and B. Lan, "Roundtable Proceedings: Ways Forward for On-Orbit Servicing, Assembly, and Manufacturing (OSAM) of Spacecraft," 2018.

Scope Title:

#### **Development of Large-Scale Additive Manufacturing Processes for On-Orbit Manufacturing**

##### **Scope Description:**

Technology development efforts are required to enable on-orbit servicing, assembly, and manufacturing (OSAM) for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets.

The ability to additively manufacture large-scale structures in-space is an enabling capability needed to fully realize the game-changing impacts of OSAM. Current state-of-the-art (SOA) on-orbit manufacturing systems are constrained to a build volume similar to terrestrial additive manufacturing processes, and others are focused on linear beam and truss designs. Structural designs for crewed habitats, space telescopes, antennas, and solar array reflectors are primarily driven by launch considerations such as payload fairing dimensions and vibrational loads experienced during ascent. Large-scale, free-form additive manufacturing capabilities can potentially eliminate constraints on the system imposed by launch, enabling the construction of larger, more complex, and more optimized structures.

This subtopic seeks innovative engineering solutions to fabricate and/or repair large structures, using fully autonomous or semi-autonomous systems, in the unpressurized space environment. Current SOA terrestrial large-scale additive manufacturing processes such as wire-fed directed energy deposition, pellet-fed extruder systems, and additive friction stir deposition should be modified with an effort to reduce the footprint, mass, and power requirements for on-orbit applications.

Phase I is a feasibility study and laboratory proof of concept of a robotic large-scale additive manufacturing process and system for unpressurized in-space manufacturing applications. Targeted applications for this technology include fabrication of truss structures, build-up of structural material for retrofitting spent tanks to habitat modules, and/or solar array back planes. Additional targeted applications include the repair of structures such as spacecrafts and/or payloads damaged during the ascent stage, habitat modules with micrometeoroid impact, and out-of-service components due to unforeseen circumstances and/or scheduled repairs. The Phase I effort should provide a laboratory demonstration of the manufacturing process and its applicability to aerospace-grade metallic materials, focusing on structures that represent the priority in-space manufacturing applications identified above. Work under Phase I will inform preliminary design of a robotic additive manufacturing process and a concept of operations for how the system would be deployed and operate in the space environment. The Phase I effort should also provide an assessment of the proposed process operational capabilities, volume, and power budget. A preliminary design and concept of operations are also deliverables under Phase I. Concepts for ancillary technologies such as post-process inspection, in situ monitoring, or robotic arms for manipulation of structures to be fabricated may also be included in the Phase I effort.

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Phase I requires a demonstration/proof of concept that (a) the system enables high-value applications of in-space fabrication of large-scale structures and (b) the system shows potential for being operated remotely with very little intervention/setup. Phase II includes finalization of the design and demonstration of a ground-based prototype system. Phase III would seek to evolve the technology toward a flight demonstration, either via a system mounted externally on the ISS, Gateway, OSAM-1, OSAM-2, a lunar lander payload, or as a free-flyer.

**Expected TRL or TRL Range at completion of the Project:** 3 to 5

**Primary Technology Taxonomy:**

Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing

Level 2: TX 12.4 Manufacturing

**Desired Deliverables of Phase I and Phase II:**

- Prototype
- Analysis
- Hardware

**Desired Deliverables Description:**

Phase I requires a demonstration/proof of concept that (a) the system enables high-value applications of in-space fabrication of large-scale structures and (b) the system shows potential for being operated remotely with very little intervention/setup. The Phase I effort should provide a laboratory demonstration of the manufacturing process and its applicability to aerospace-grade metallic materials, focusing on structures that represent the priority in-space manufacturing applications identified above. The Phase I effort should also provide an assessment of the proposed process operational capabilities, volume, and power budget. A preliminary design of a robotic additive manufacturing process and a concept of operations for how the system would be deployed and operate in the space environment are also deliverables under Phase I. Concepts for ancillary technologies such as post-process inspection, in situ monitoring, or robotic arms for manipulation of structures to be fabricated may also be included in the Phase I effort.

Phase II includes finalization of the design and demonstration of a ground-based prototype system including autonomous capability.

Phase III would seek to evolve the technology toward a flight demonstration, either via a system mounted externally on the ISS, Gateway, OSAM-1, OSAM-2, a lunar lander payload, or as a free-flyer.

**State of the Art and Critical Gaps:**

Unpressurized structure in-space manufacturing has primarily focused on fabrication of 3D-printed truss structures and beams. The OSAM-1 and OSAM-2, funded by the STMD (Space Technology Mission Directorate) Technology Demonstration Mission Program, are planning the demonstration of 3D-printed truss structures and beams. The technology advancement to multiple degrees of freedom, large-scale fabrication of structures is a priority for on-orbit manufacturing.

**Relevance / Science Traceability:**

The research requested through this solicitation is relevant to NASA programs, including (but not limited to) the following: ISS, Exploration Crew Module, Gateway, Lunar Base Camp, OSAM-1, OSAM-2 and in-Space Assembled Telescope (iSAT).

**References:**

R. G. Clinton, Jr., "NASA's In Space Manufacturing Initiatives: Conquering the Challenges of In-Space Manufacturing," 2017. [Online]. Available: <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170011108.pdf> [Accessed: 10-Oct-2019].

I. D. Boyd, R. S. Buenconsejo, D. Piskorz, B. Lal, K. W. Crane, and E. De La Rosa Blanco, "On-Orbit

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Manufacturing and Assembly of Spacecraft: Opportunities and Challenges," 2017.

S. Carioscia, B. A. Corbin, and B. Lan, "Roundtable Proceedings: Ways Forward for On-Orbit Servicing, Assembly, and Manufacturing (OSAM) of Spacecraft," 2018.

Scope Title:

#### **Development of Metal Recycling Processes for On-Orbit Manufacturing**

##### **Scope Description:**

Deep space missions will require a shift in the logistics paradigm to enable reuse and recycling of materials. Recycling is a significantly enhancing capability for space missions and would enable what would otherwise be nuisance material (spent components, waste items) to be utilized as feedstock for further manufacturing. This subtopic seeks innovative engineering solutions to facilitate recycling of metals commonly used in space systems in either an intravehicular (IVA) or extravehicular (EVA) environment. In an IVA use scenario, technologies might be used inside a habitat to process spent components by breaking down the structure, generating chips, and consolidating the chips into feedstock that can be used to generate new components through various in-space manufacturing processes. In an EVA use scenario, recycling technologies might be used to take metal material scavenged from large structures (such as space habitats, satellites, and spent upper stages) and reprocess it into material feedstock for on-orbit servicing, assembly, manufacturing, and repair applications. High-value materials for metal recycling include those commonly used in large-scale space structures and components of space systems: aluminum alloys, stainless steel, and titanium.

Current state of the art (SOA) includes metal recycling technologies commonly applied in industry (e.g., shredding, melting, solidification), but these must be modified to fit the physical footprint, power, and mass requirements for on-orbit applications. For an IVA environment, the system for initial demonstration would be constrained to an EXPRESS\* rack, occupying some portion of its 0.45-m<sup>3</sup> volume. An EXPRESS rack is designed to support up to eight individual payloads, each occupying one EXPRESS locker (each locker has an internal volume of approximately 0.057 m<sup>3</sup>, with the total rack of eight lockers providing in excess of 0.45 m<sup>3</sup> of payload volume). The width of a single locker is 0.44 m, the height is 0.25 m, and the depth is 0.52 m. The full rack can accommodate approximately 260 kg. In an EVA environment, the metal recycling capability would likely operate as a free-flyer platform.

\*EXPRESS is an acronym for "EXpedite the PROcessing of Experiments to the Space Station."

**Expected TRL or TRL Range at completion of the Project:** 3 to 5

##### **Primary Technology Taxonomy:**

Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing

Level 2: TX 12.1 Materials

##### **Desired Deliverables of Phase I and Phase II:**

- Analysis
- Prototype
- Hardware

##### **Desired Deliverables Description:**

Phase I is a feasibility study and proof of concept of a system for in-space recycling of one or more metal materials. Targeted applications for the technology include processing of spent components into feedstock for in-space manufacturing and/or processing of large-scale structures (such as spent upper stages) into material forms for further use. While the focus should be on material processing (which may include shredding, melting, solidifying, and other processes necessary to obtain a final feedstock form), other ancillary techniques such as sorting,

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purification, and material delivery/transport may also be considered as part of an overall concept of operations. How the system will be deployed and operated in either an IVA or EVA environment should also be considered. The Phase I effort should also include a laboratory demonstration of the core recycling technique with an aerospace-grade metallic material and some characterization of properties post-recycling. Relevant metrics such as power consumption, system footprint, and mass of system should also be reported, with an emphasis on scalability and adaptation to the relevant space environment. This work will collectively inform preliminary design of a metal recycling capability for in-space use. An additional constraint is that the system must be operated remotely with very little intervention/setup. Even in an IVA environment with crew, the availability of crew time to tend or service a recycling system will be very limited. An EVA environment would require fully remote operation.

Phase II would include finalization of the design and demonstration of a ground-based prototype system.

Phase III would seek to evolve the technology to a flight demonstration for ISS (internal or external payload) or as a free-flyer.

#### **State of the Art and Critical Gaps:**

The current SOA is terrestrial systems for metal recycling, but these processes must be adapted to operate in the relevant space environment and comply with the system constraints of their intended use (for example, in an IVA environment as a payload). The capability to break down spent components and larger structures and repurpose them into a useful product is needed on long-duration space missions where logistics are constrained. Recycling of polymer materials on the International Space Station (ISS) into manufacturing feedstock (for 3D printing) has been previously demonstrated, but there are no current recycling capabilities for metals on the ISS. For external applications of metal recycling, NASA has funded some Next Space Technologies for Exploration Partnerships (NextSTEP) work previously on repurposing of spent rocket stages left in-orbit. Recycling, reuse, and repurposing of metals is seen as a critical gap for on-orbit servicing, assembly, and manufacturing (OSAM) and shifting the logistics paradigm from pre-positioning of spare parts to point-of-use manufacturing.

#### **Relevance / Science Traceability:**

The research requested through this solicitation is relevant to NASA programs, including (but not limited to) the following: ISS, Exploration Crew Module, Gateway, Lunar Base Camp, OSAM-1, OSAM-2 and in-Space Assembled Telescope (iSAT).

#### **References:**

T. Prater et al., "In-Space Manufacturing at NASA Marshall Space Flight Center: A Portfolio of Fabrication and Recycling Technology Development for the International Space Station," 2018.